Hydrodynamics and Sediment Transport in a
Macro-tidal Estuary: Darwin Harbour, Australia

F.P. Andutta, X.H. Wang, Li Li, and D. Williams

Abstract

Sediment dynamics studies were undertaken for Darwin Harbour (DH), which is a tidal dominated mangrove system in the Northern Territory of Australia. DH is located in a region with extensive mangrove and tidal flat areas, which function as trapping zones of fine cohesive sediment. Transport of sediment was estimated for the dry season, and thus river discharge was negligible. Numerical simulations were also made with two scenarios: (S₁) where the numerical mesh included mangrove and tidal flats, and (S₂) in which the mesh neglected these areas. For the first scenario, the formation of two Estuarine Turbidity Maxima zones (ETM) were verified, and located at the inner and outer harbour. In addition to the formation of ETM zones, for the second scenario increased tidal asymmetry was predicted, which resulted in landward sediment transport. The suspended sediment concentration within these ETM zones was modulated by spring and neap tidal conditions. From our simulations we demonstrated that the sediment transport of small particles, e.g. 2 µm particle size, in DH is driven by flood dominance, which is affected by wet/dry areas such as mangroves and tidal flats. Therefore, mangrove areas of DH may trap fine sediment for long periods, and if the trapped sediment carries pollutants one would expect conditions similar to many European estuaries, where pollutant sediment has been found to be buried for over tens to hundreds of years.

Keywords

Darwin Harbour • Tropical estuary • Dry season • Macro-tides • Sediment transport • Flood dominance • Hydrodynamic modelling • Sediment transport modelling

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Box 1

Fernando Andutta and colleagues studied Darwin Harbour. They focused on modelling the sediment dynamics studies in order to understand how the estuary will change with developments in the catchment. They demonstrated that the sediment transport of small particles is driven by flood dominance, which is affected

by wet/dry areas such as mangroves and tidal flats. Therefore, mangrove areas of Darwin Harbour may trap fine sediment for long periods, and if the trapped sediment carries pollutants one would expect conditions similar to many European estuaries, where polluted sediment has been found to be buried for tens to hundreds of years.

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Introduction

25 The understanding of sediment transport is important to the
26 development and management of harbours and many other
27 sea-structures. The top 15 cities of Australia in terms of
28 largest population are located along the coast (aside
29 from Canberra), and often near estuaries and harbour areas
30 (e.g. Sydney, Perth, Melbourne, Adelaide, Darwin and
31 Townsville). These 15 cities contain over 80 % of Australia's
32 total population in 2012, which means over 17 million people

are currently living in areas near estuaries, bays and harbours. 33
The large number of people living in these transitional areas 34
between land and the ocean (e.g. estuaries) results in a signif- 35
icative human impact on coastal aquatic environments 36
(Harvey and Caton 2010). Because of this, the understanding 37
of erosion, deposition and sediment transport processes 38
should be relevant for the majority of Australians. It should 39
be noted that coastal management may have different 40
definitions, which sometimes vary according to different 41
cultures, countries and even the perspective of view of 42
an author. Harvey and Caton (2010) defined coastal 43

management as the management of human activities and the sustainable use of coastal resources in order to reduce adverse impacts on coastal environments in the present and in the future. This definition means a complex integrated approach is necessary, as it is not possible to treat the coastal land and the coastal water as individual ecosystems. Both are interconnected systems, and therefore interconnected management is important.

The development of cities around ports is often associated with the expansion of ports and activities such as oil, coal, and gas exportation (e.g. Gladstone Port, Abbott Point, Hay Point, Port Kembla, Darwin Harbour). These activities result in multiple environmental stresses, such as dredging to facilitate the navigation of larger ships, land reclamation, and changes in the sediment and nutrient runoff to catchment areas (Andutta et al. 2006b; Wang and Pinardi 2002). Treated sewage from coastal cities in Australia is discharged into estuaries, rivers, beaches and coastal waters. As a result, hotspots of water pollution have been observed to be linked to coastal cities, which are releasing industrial wastes, rubbish through wastewater systems, sediments, heavy metals, nutrients etc. (Zann and Kailola 1995). Additionally, some anthropogenic impacts may even reach extremely important marine ecosystems, for example the fine coal dust observed to reach the southern area of the Great Barrier Reef (GBR) (Burns and Brinkman 2011), and was predicted using numerical modelling simulations by Wolanski and Andutta (Frazer 2012).

The increase in mud concentrations in coastal waters is a worldwide ecological issue that can negatively affect many marine organisms, for example limiting the growth of phytoplankton at the subsurface, and the growth of pearl farms (e.g. pearl farms near Darwin and Broome). Wolanski (2007) observed that many historical sandy coasts around Australia had been replaced by muddy coasts, and this change is envisaged as a permanent degradation (unlikely to be naturally reversed). Recreational and maritime activities can be adversely impacted by processes of sediment resuspension and deposition, and this can lead to economical loss. For example, a possible reduction of coral reefs near Cairns would decrease appeal to eco-tourism, and therefore impact the local economy. Marine sediment may also carry nutrients and pollutants from land sources to coastal waters, transporting these substances through areas where numerous marine species reproduce, e.g. bays and estuaries. An understanding of sediment transport leads to a better comprehension of pollution control, helping to preserve the marine ecosystem through integration with coastal management system (e.g., Frascari et al. 1988; Giordani et al. 1992).

The spatial and temporal variability of the transport of sediment also has hydrographical implications, such as sediment deposition in navigable channels. For some estuarine

systems, dredging maintenance can be really expensive e.g. Yangtze Estuary (Wu et al. 2009; Liu et al. 2011), where over 100 million m³ of sediment has been dredged per year from 2006 to 2008. The dynamics of sediment transport depend on water circulation, salinity concentration, biological interaction, and sediment type. For estuaries, sediment distribution is often comprised of cohesive sediment (e.g. clay and mud), and non-cohesive sediment (e.g. sand). Cohesive sediments are usually transported in the water column, because they are easily suspended by water currents. Alternatively, non-cohesive sediments are mainly transported along the bottom by the processes of rolling, saltation, and sliding. However, under some circumstances, sediment can be transported along the bed as a bottom fluid sediment layer (Puig et al. 2004).

The study of sediment transport in coastal aquatic systems is usually complex because of complex geometry, many sediment types, and many boundary forcing mechanisms such as tides, wind, river discharge, density-driven currents etc. Sediment transport research has always received attention (e.g. Kessel et al. 2011; Margvelashvili et al. 2003; Allen et al. 1980), and also has implications on contaminant behaviour. Toxic substances, e.g. metals, tend to associate with fine sediment particles, which are potentially the most mobile sedimentary fraction under normal energy conditions of the system (Taylor and Hudson-Edwards 2005, 2008; Thonon 2006). Estuaries often have high sediment concentrations in the water column, e.g. macro tidal estuaries, and the overall sediment transport can be upstream for some particular systems (e.g. Margvelashvili et al. 2006). Some of the many physical processes affecting estuaries are: (1) settling lag and scour lag effects (van Straaten and Kuenen 1958; Postma 1961); (2) shoaling tidal waves that cause an asymmetric distribution of velocity and suspended sediment concentration, known as tidal pumping (Dyer 1986); (3) vertical velocities associated with flocculation and hindering (Pejrup 1988); (4) bed-load transport and bed solidification and liquefaction (Kessel and Kranenburg 1998; Maa and Mehta 1987). To add complexity to the understanding of the hydro-dynamical and morphological changes in many aquatic systems, the combined effect of headlands, rivers, and embayments creates a complicated bathymetry that leads to the formation of many tidal jets within narrow channels, eddies etc.

This manuscript addresses the study of sediment transport within Darwin Harbour (DH), which is an embayment next to Shoal Bay (SB), see Fig. 1a. DH extends from Charles Point to Lee Point. Some previous studies define Darwin Harbor to be the area extending from Charles Point to Gunn Point, which comprises the water area of Shoal Bay. However, a harbour by definition is any natural or artificial place where vessels may seek shelter from stormy weather, and thus Shoal Bay is not part of DH. Harbours differ from bays

Fig. 1 (a) Map of Australia showing the location of DH in the Northern Territory (NT), and indication of Shoal Bay. Areas of mangroves and tidal flats, and indication of Blaydin Point in EA. Adelaide River is located near Shoal Bay on the right side (not shown in this map). (b) Browse Basin and indication of Ichthys Field with gas pipeline extending to Darwin Harbour

this development, stakeholders required an assessment of the potential impacts on many local marine species, e.g. mud crabs, and the likely consequences of elevated suspended sediment concentration in DH (Fig. 1). The project by INPEX was approved in 2012, and an operation to dredge a shipping channel in DH started at the end of 2012, and is expected to take less than 2 years to complete. INPEX is bringing in the largest dredge ship ever seen in Australia to start the dredging operation, which will reduce the previously estimated time of 4 years to only ~15 months. On completion, the harbour will have a deeper channel for liquefied natural gas (LNG) carriers to load gas at a multi-billion dollar processing plant being built at Blaydin Point (in EA).

Although DH is of great economic importance to the Northern Territory (NT), most of the current knowledge about the main driving forces for the local hydrodynamics is due to efforts by numerous researchers (Li et al. 2011, 2012; INPEX 2010a, b; Williams 2009; Wolanski et al. 2006; Williams et al. 2006; Williams and Wolanski 2003; Padovan 2003; Ribbe and Holloway 2001). Williams (2009) used a 2D sediment model to assess changes in sediment transport if the sandbar in the EA is removed. Li et al. (2012) used a 3D hydrodynamical model of DH (see Fig. 1), and verified the effect that the mangrove and tidal flat areas have on the tidal asymmetry. It was predicted that a decrease in area of the tidal flats and mangroves would lead to increased tidal asymmetry of flood dominance. Evidently, such changes in water circulation lead to changes in the local redistribution of sediment, e.g. different patterns of erosion and deposition areas. This manuscript also concurs with the study by Li et al. (2012), using the same 3D hydrodynamical model, i.e. Finite Volume Community Ocean Model (FVCOM). Aside from the modelling by Li et al. (2012) and Li et al. (2011), previous hydrodynamical models of DH were often vertically integrated (e.g. INPEX 2010a, b). For DH, vertically integrated models have always simulated water circulation properly. This is because tidal currents prevail over small baroclinic currents (INPEX 2010a, b), especially during the dry season. However, suspended sediment concentration varies along the water column, and thus small changes in horizontal currents in the water column might be important for sediment dynamics. Our model is a fully 3D hydro-sediment model using an unstructured mesh, and thus capable of capturing these small current changes within the many layers. The 3D hydrodynamical model was coupled to a sediment model that uses the density induced stratification according to Wang (2002). Other physical mechanisms were also included and will be discussed further in detail. The role that tidal flats and mangrove areas play on the transport of cohesive fine sediment (e.g. 2 μm particle size) was analysed, and some of the physical mechanisms for sediment transport were quantified, e.g. tidal pumping, residual circulation, Stokes drift etc.

in that a bay describes a geographical feature, while a harbour is defined by its function. We focused on sediment transport studies and the formation of Estuarine Turbidity Maxima zones (ETM) within DH. Some physical mechanisms affecting sediment transport in DH were investigated, as well as their implications on net sediment flux and distribution of ETM zones. Additionally, the likely future of DH due to the expansion of port activities is discussed. Currently, dredging in DH is present ~16 days per year, resulting in a dredged volume of ~50,000 m^3 from East Arm (EA) (Australian Natural Resource Atlas).

For the East Arm in DH, INPEX Browse Ltd (INPEX) is undertaking the Ichthys Gas Field Development to extract liquefied gas from Browse Basin, see Fig. 1b. The project requires the development of onshore, nearshore and offshore infrastructures. In addition, nearly 15 million cubic metres of mainly hard soil will be dredged in DH by Van Oord Ltd. (Sinclair Knight Merz Pty Ltd. 2011). To obtain approval for

Darwin Harbour Description

DH is a semi-enclosed estuarine system with extensive mangrove areas (Fig. 2c), in which wind wave activity is sufficiently diminished to allow the development of a harbor and recreational facilities (Makarynskyy et al. 2011). Economic activities of DH are all located along-side the EA, Fig. 2a, b. Depths in DH range from 0 to 20 m, with a maximum of up to ~40 m in coastal areas. DH is located in the Northern Territory (NT) of Australia, and its surrounding lands are occupied by the cities of Palmerston and Darwin. DH is the embayment next to Shoal Bay (see Fig. 1). The two largest economic sectors in Darwin city and the surrounding areas are the mining and tourism industries (exceeding \$2.5 billion per annum), which are currently attracting people from around Australia and overseas to migrate to this region. Between 2000 and 2001, exploratory research resulted in the discovery of an extremely promising gas and condensate

field, which is the Ichthys Field located at Browse Basin. The Ichthys Project will have an initial capacity to produce 8.4 million tonnes of Liquid Natural Gas (LNG) per annum, and 1.6 million tonnes of liquefied petroleum gas (LPG) per annum, as well as approximately 100,000 barrels of condensate per day at peak (Kelly 2012). After preliminary processing at the offshore central processing facility (CPF), the gas will be transported from the CPF through a subsea pipeline more than 885 km to the onshore LNG processing plant proposed for Blaydin Point on Middle Arm Peninsula, Darwin, Northern Territory. It will be cooled to below minus 161 °C, the point at which the gas becomes a liquid, known as LNG. Nearly AUD \$34 billion has been formally opened by the Australian government for the Ichthys liquefied natural gas project in Darwin in May 2012. The Northern Territory Government has approved development of a Village, which will accommodate 3,500 anticipated workers at the peak of onshore construction. The Howard Springs Accommodation Village is being developed to house the fly-in

Fig. 2 (a) EA wharf, mangroves dark red, extensive intertidal mudflats, (b) Sediment plumes, looking from Charles Darwin national park to Darwin city, (c) mangroves from Middle Arm

fly-out workforce required to build the Ichthys gas processing facilities at Blaydin Point, Darwin (Kelly 2012). The Ichthys Project is expected to start production by the end of 2016.

As economic activity increases, so will population (Fig. 3). For Darwin city (Fig. 2b), the population is predicated to be between ~170 and ~335 thousand people by 2056. Consequently, an increase in natural resource usage and anthropogenic stress on the terrestrial and aquatic environments is almost inevitable. Of all the estuarine systems located near capital cities of Australia, DH (near Darwin city) was the only system classified as largely unmodified by 2002 (Estuary Assessment 2002: Estuaries by Australian Natural Resources Atlas). This condition is, however, likely to change in the next couple of years due to port expansion, and later due to the increasing use of natural resources, which is associated with the predicted population increase (see prediction in Fig. 3).

DH contains the West Arm (WA), Middle Arm (MA) and East Arm (EA) catchments (Fig. 1). The major freshwater inputs for DH are predominantly from the Elizabeth River

(for EA), Berry Creek, and Blackmore and Darwin Rivers (for M A). For WA, the fresh water input is considered relatively small compared to the other arms. For the embayment next to DH, i.e. Shoal bay, the fresh water input is from Howard River (Wilson et al. 2004). In DH evaporation usually exceeds rainfall throughout the year, except during the wet season. During the dry season, fresh-water input into DH is negligible and evaporation exceeds river discharge (Avg. Rainfall in Table 1). As a result, in the dry season, salinity concentrations in DH usually become 0.8 psu higher than the adjacent coastal waters (Padovan 1997, 2003), and DH becomes a hypersaline system like many others in Australia (e.g. Andutta et al. 2011, 2012, 2013a). Michie et al. (1991) reported that from September to October the salinity in DH is typically 35 psu, and the lowest salinity values coincide with the wet season, with values of 5 psu observed in the further upper reaches of MA. From February to October, the evaporation rate varies between 170 and 270 mm, with an average annual evaporation rate of ~2,650 mm. Tropical savannah is the predominant climate of the region, with a mean temperature of ~28 °C (Monthly avg. temperatures in Table 1), which slightly decreases during winter to ~23 °C, and increases during summer to ~32 °C. Water surface temperature during June-July is ~23 °C (winter), ~33 °C during October-November (summer), followed by a small decline of ~4 °C from December to February due to the wet season (Padovan 2003). Michie et al. (1991) reported that temperatures from the inner harbour to the upstream location in MA showed very little spatial change. Located in a subarid/humid area, DH has a typical rainfall of 1,700 mm year⁻¹ (2,500 mm in exceptionally wet years), see Table 1. Runoff typically varies between 100 and 750 mm year⁻¹, with the maximum occurring during the wet season (Wang and Andutta 2012; Milliman and Farnsworth 2011).

DH is forced by semi-diurnal tides, and is classified as a macro-tidal estuary with the form number $N_f = 0.32$ (criteria of A. Courtier of 1938; Defant 1960). The maximum observed tidal range is ~7.8 m, with mean spring and neap tidal ranges of ~5.5 and ~1.9 m, respectively (Wang and Andutta 2012; Li et al. 2011, 2012; Milliman and Farnsworth 2011; Woodroffe et al. 1988; Michie 1987).

Fig. 3 Historical data of the population of Darwin city from 1911 to 2010 (thicker line), and the projections from cases A, B and C cover the period from 2010 to 2056. Different assumptions about level of fertility, mortality, internal migration and overseas migration were taken into account (Source: Australian Bureau of Statistics)

Table 1 Climate data obtained at Darwin Airport station (data from 1941 to 2012) indicating monthly average (Avg.)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Record high °C	35.6	36.0	36.0	36.7	36.0	34.5	34.8	36.0	37.7	38.9	37.3	37.0	38.9
Avg. high °C	31.8	31.4	31.9	32.7	32.0	30.6	30.5	31.4	32.6	33.2	33.3	32.6	32.0
Avg. low °C	24.8	24.7	24.5	24.0	22.1	19.9	19.3	20.4	23.0	24.9	25.3	25.3	23.2
Record low °C	20.2	17.2	19.2	16.0	13.8	12.1	10.4	13.2	14.3	19.0	19.3	19.8	10.4
Rainfall mm	426.6	374.3	321.3	101.2	21.2	1.9	1.2	5.0	15.7	71.0	140.2	252.0	1,731.6
Avg. rainy days	21.4	20.4	19.6	9.3	2.2	0.6	0.5	0.6	2.3	6.7	12.4	16.8	112.8

Source: Climate statistics for Australian locations, October 2012

This tidal range is relatively large compared to the mean depth, and therefore the potential energy from sea level oscillation can easily diminish vertical stratification. The DH area comprises numerous mangroves and tidal flats. Nearly 5 % of the whole mangrove area in the Northern Territory belongs to DH, i.e. $\sim 274 \text{ km}^2$ (Brocklehurst and Edmeades 1996; Tien 2006).

Wind conditions for DH do not vary much within a spatial scale of a few tens of kilometres (INPEX 2010a, b). Therefore, homogeneous wind conditions are considered representative and can be applied in numerical simulations. Tropical cyclones may occur in this area during the wet season, and winds are predominantly from the east (in the range of $\sim 160^\circ$ to $\sim 200^\circ$, i.e. winds from NW and SW). During the wet season, $\sim 17\%$ of the easterly wind speed is in the range of $7.5\text{--}10 \text{ m s}^{-1}$. The most frequent wind speed in the wet season is $\sim 9 \text{ m s}^{-1}$; however, characteristically extreme wind conditions are $\sim 18 \text{ m s}^{-1}$. In contrast, during the dry season, SE winds prevail (in the range of $\sim 325^\circ$ to $\sim 360^\circ$, i.e. winds from SE), and $\sim 19\%$ of the E-SE wind speed is in the range of $7.5\text{--}10 \text{ m s}^{-1}$. The most frequent wind speed in the dry season is $\sim 9.3 \text{ m s}^{-1}$, but characteristically extreme wind conditions are $\sim 14 \text{ m s}^{-1}$ (INPEX 2010b). During intense cyclones the wind can reach speeds of up to $\sim 60\text{--}70 \text{ m s}^{-1}$, e.g. cyclone Tracy in 1974.

Wave conditions for DH are reported to have a small effect when compared to its macro-tidal currents. INPEX (2010b) provided some numerical simulations for different wave conditions. Typical moderate and high energy wave conditions were applied, from N and NW directions and periods of 5 and 10 s. They concluded that wave energy reduces landwards, and wave bottom stress is usually less than 0.1 N m^{-2} inside the bay (aside from shallow areas near the bay entrance).

The mean depth at the inner part of Darwin Bay is in the range of ~ 15 to 20 m . If one considers the average depth to be $\bar{H} = 15 \text{ m}$, wavelengths λ larger than 30 m would affect bottom stress. The exact formula of the phase speed of gravity (C_w) is $C_w = [(g\lambda/2\pi) \tanh(2\pi\bar{H}/\lambda)]^{1/2}$ or $C_w = \lambda/T$, where T is the wave period and g is the gravity acceleration. Therefore, the period is expressed by $T = [(2\pi\lambda/g) \tanh^{-1}(2\pi\bar{H}/\lambda)]^{1/2}$; thus, areas shallower than 10 m would be affected by waves of periods larger than $T \sim (4.3 + 3.5i)$, i.e. absolute value of $\sim 5.6 \text{ s}$. Evidently, bottom stress is just one of the different wave effects on sediment transport. For DH, one would consider the effect from the build-up of pore pressure within the sediment, which causes bed liquefaction and contributes to bed-load transport (Kessel and Kranenburg 1998; Maa and Mehta 1987). However, it is likely that the currents from the macro-tides within DH dominate erosion of sediment from the bottom, and thus overcome the effect of bottom liquefaction. The only

optimum condition to enable the build-up of pore pressure in DH would be times of high or low tides coinciding with times of wind-waves occurring at the harbour entrance.

Model Description, Configuration and Calibration

To simulate the hydrodynamics and transport of sediment for DH, the unstructured numerical model FVCOM was applied (Chen et al. 2003). FVCOM is a three-dimensional hydrodynamic model using unstructured, finite element mesh. Two numerical meshes were applied, the first mesh (9,666 horizontal cells) contained both tidal flats and mangrove areas, and the second mesh (3,607 horizontal cells) excluded these areas. For both meshes the horizontal resolution varied between $\sim 20 \text{ m}$ and $\sim 3,300 \text{ m}$ (Fig. 4). The increased horizontal resolution was applied in the inner harbor, while the lower horizontal resolution was applied in the coastal area. Twenty vertical sigma layers were used. Higher vertical resolution was applied for the layers near the surface and bottom. The bathymetry data was obtained from Australian Institute of Marine Sciences (AIMS). Figure 3b shows that the generated mesh is adequate to simulate the hydrodynamics of DH, because it covers all mangroves and tidal flat areas, which are treated as wet/dry cells with higher bottom friction.

Boundary Forcings

Tidal components were used to force the model at the external open boundary, i.e. the coastal zone. These components were obtained from the TPXO7.2 global model for ocean tides (<http://volkov.oce.orst.edu/tides/TPXO7.2.html>). The diurnal tidal components applied at the open boundary were K_1 , O_1 , P_1 and Q_1 , and the semi-diurnal tidal components were M_2 , S_2 , N_2 and K_2 . Additionally, the components M_4 , MS_4 , MN_4 , M_f and M_m were used. These tidal components represent over 99 % of sea level variations for all of the DH area (Wang and Andutta 2012; Li et al. 2012). Hourly sea surface elevation data from 1991 to 2010 from the station of the Bureau of Meteorology (BoM, Fig. 3) were analysed to study the principal tidal characteristics of the harbour, and used to validate the model results. Additionally, data of sea surface elevation from AIMS was used to validate the model (Blaydin station, Fig. 4).

The drainage basin of DH covers $\sim 1,833 \text{ km}^2$, and the surface water in low tide is $\sim 863 \text{ km}^2$, resulting in a total surface area of $\sim 2,696 \text{ km}^2$ (Wang and Andutta 2012; Li et al. 2012), which is smaller than the drainage basin from

Fig. 4 (a) DH domain with indication of water, mangrove and tidal flat areas. Grid elements over mangrove and tidal flat areas are wet/dry elements. (b) Numerical grid of DH with resolution from about 20 m to 3.3 km, and colours to indicating water area (blue), tidal flats (pink) and mangrove areas (green). Indication of data extract from

transects *i*, *ii* and *iii* from simulations. (c) Location of field measurements of tides, salinity, temperature, and water currents. Detailed description is shown in method section in Table 2. Different scales were used for the vertical and horizontal axes, and view is on a plan surface

the nearby Adelaide River ($\sim 7,600 \text{ km}^2$). The annual discharge from the Adelaide River is $\sim 2 \text{ km}^3/\text{year}$ ($\sim 63 \text{ m}^3 \text{ s}^{-1}$) (Milliman and Farnsworth 2011). Taking into account a negligible spatial variation of rainfall over the drainage areas of DH and Adelaide River, the annual mean river discharge for DH is roughly estimated using $Q = \alpha 360$ (where $\alpha = 2696/7600$ is the ratio between both catchments), thus the annual mean river flow for DH would be $\sim 22 \text{ m}^3 \text{ s}^{-1}$. Data obtained from telemetered gauging stations in DH, Shoal Bay and Adelaide River area were evaluated. Flow discharge monitored at most stations within

these areas show high correlation. The high correlation of measured river flow indicates the rainfall conditions within these areas are similar. The stations compared were G8150018 (Elizabeth River), G8150322 (Bennetts Creek), G8150036 (Bees Creek), G8150098 (Blackmore River), G8150028 (Berry Creek), G8150321 (Peel Creek), G8150179 (Howard River) for DH (in Fig. 1), and stations G8170085 (Acacia Creek), and G8170020 (Adelaide) for Adelaide River (location not shown in Fig. 1). Evidently, $\sim 22 \text{ m}^3 \text{ s}^{-1}$ is a rough estimate that implies that these drainage basins have similar vegetation distribution,

Fig. 5 Estimated monthly mean river flow Q for DH, and the annual mean discharge of $29 \text{ m}^3 \text{ s}^{-1}$

of the Harbour, which is 6,000 m wide and 20 m deep, this flow would result in residual currents of $\sim 10^{-3} \text{ m s}^{-1}$. This indicates that the residual circulation and baroclinic circulation due to river discharge is likely to be more important at the further upstream areas along the EA, MA and WA.

For the internal boundaries of DH, e.g. upstream river zones, there are three main sources of fresh water in the domain (Elizabeth River, Blackmore River and Berry Creek); however, the simulation was for the dry season and thus river discharge was negligible (Wang and Andutta 2012; Li et al. 2012; DHAC 2003; Burford et al. 2008). The monthly estimate of fresh water inflow for DH shows negligible inflow for the dry season (Fig. 4). In the dry season, the baroclinic circulation due to the horizontal salinity gradient is often confined to a few upstream areas in DH (INPEX 2010a, b), and these baroclinic currents are usually less than 3 % of the maximum tidal current intensity (Li et al. 2012). The temperature field was also reported to have little spatial variation (Michie et al. 1991), and to have little seasonal variation (observed from data at BoM station from 01/05/1991 to 31/12/2010). Therefore, salinity and temperature have a negligible effect on water circulation during the dry season.

At the surface, the wind is sometimes an important mechanism that causes sediment resuspension in estuaries by wind-driven currents and wind-driven waves (Mehta 1988). However, as previously discussed for DH, the wind was observed to have a negligible effect compared to tidal currents (Li et al. 2012; INPEX 2010a, b). Tides dominate the transport of sediment with currents of up to $\sim 2.5 \text{ m s}^{-1}$, with typical tidal oscillation between 3.7 and 7.8 m (Wang and Andutta 2012; Li et al. 2012). In summary, the effects from wind-driven currents, wind-driven waves, river discharge, and the heat flux at the sea surface were negligible, resulting in simulations only forced by tides.

Physical and Numerical Parameters

Bottom sediment distribution in DH consists predominantly of small particles, which are often transported through the water column. Therefore, this study only considers the transport of suspended sediment (TSS) and neglects the bed load transport of sediment. The equations by Wang (2002) were used to calculate TSS. Because salinity and temperature were assumed to be constant, only sediment concentration would affect water density. The water density (Eq. 1) was calculated assuming the volumetric relation,

$$\rho = \rho_w + \left(1 - \frac{\rho_w}{\rho_s}\right)C, \quad (1)$$

evapotranspiration, soil permeability, ground water etc. Rainfall usually varies in space and time, and thus a limited number of rainfall stations over the drainage basin may have an impact on runoff estimates (Sun et al. 2010). Nevertheless, this estimate provides a reasonable mean annual flow for DH, which is likely to differ by an acceptable percentage from the actual DH runoff. A different approach to estimate the river discharge for DH is to use the average runoff and groundwater of 500 mm/year, combined with the drainage basin area of $1,833 \text{ km}^2$, which results in an annual average discharge of $\sim 29 \text{ m}^3 \text{ s}^{-1}$. Note that this estimate is close to the previous estimative of $\sim 22 \text{ m}^3 \text{ s}^{-1}$.

The river discharge in DH is controlled by rainfall; therefore, the climate data obtained for over 70 years is important information that can be used to estimate the average runoff in each month (See Table 1). Consider the annual estimated river discharge from runoff and groundwater to be $Q_e \sim 29 \text{ m}^3 \text{ s}^{-1}$ (as described previously), where the mean river flow per month, Q_m , is estimated using the factor $\beta = R_m/R_a$ in equation $Q_m = Q_e \beta$, where R_a is the monthly mean rainfall, and R_y is the annual mean rainfall. The estimated monthly average discharge for DH is shown in Fig. 5, which can be used in simulations under typical conditions for DH. From May to October, which is a period that covers the dry season, the mean river flow into DH is smaller than $15 \text{ m}^3 \text{ s}^{-1}$. In contrast, from December to March, which is typically the wet season, the river flow usually exceeds $50 \text{ m}^3 \text{ s}^{-1}$. Although the mean river discharge is estimated to increase to $\sim 85 \text{ m}^3 \text{ s}^{-1}$ in January, for the dimensions of DH, this flow would result in relatively small residual circulation except for the upper reaches of the three arms. In addition, for the main entrance

where C [kg m^{-3}] is the sediment concentration, (ρ_w) [kg m^{-3}] is the water density calculated by the equation of state by Mellor (1998), and (ρ_s) is the sediment dry density (assumed to be $1,250 \text{ kg m}^{-3}$).

The bottom drag coefficient (C_d) was set to be a function of the water depth for water areas, mangroves and tidal flats (see Eq. 2). The bottom drag coefficient also depends on bottom roughness length, z_0 , which is often considered a user-defined free parameter, although there have been some studies showing the space and time dependence of the z_0 parameter (e.g. Cheng et al. 1999; Xu and Wright 1995; Ling 1976; Ling and Untersteiner 1974). z_0 was assumed to be 0.035 m for water and tidal flat areas, and 0.15 m for the mangrove areas, which are reasonable values to be applied for these areas (Straatsma 2009). Higher bottom roughness length was applied in mangrove areas, because of the influence of roots and trees that significantly increase the friction and thus reduce water speed (Mazda et al. 1997). From empirical experiments within mangroves, C_d was observed to vary between 1 and 10, depending upon tidal conditions, mangrove species, mangrove density (i.e. degree of aggregation of mangroves), and patchiness of mangrove distribution. Therefore, a maximum value for C_d was established because calculated values of C_d increase to unrealistic values when water depths are too small, c.a. few centimetres (see Eq. 2).

$$C_d = \min \left\{ \left[\frac{1}{k/(1 + AR_f)} \ln \left(\frac{z_b}{z_0} \right) \right]^{-2}, 10 \right\}, \quad (2)$$

where A is an empirical non-dimensional constant; Adams and Weatherly (1981) determined $A = 5.5$ for a sediment-laden oceanic bottom boundary layer. R_f is a flux Richardson number by layer, and in this case for the bottom sigma layer. z_b is the distance to the computational grid point closest to the bed, and K is the Von Kármán constant, c.a. ~ 0.4 (Telford 1982; Orszag and Patera 1981).

The erosion rate was assumed to be higher than $5 \times 10^{-6} \text{ kg m}^{-2} \text{ s}^{-1}$ for permanent water areas, and assumed to be lower than $1 \times 10^{-7} \text{ kg m}^{-2} \text{ s}^{-1}$ for tidal flats and mangrove areas, because of the influence of roots and trees that inhibit erosion in mangrove areas (Mazda et al. 1997). Equations by Ariathurai and Krone (1976) were used to calculate the vertical sediment flux, E [$\text{kg m}^{-2} \text{ s}^{-1}$], i.e. erosion and deposition.

$$E = \begin{cases} E_0 \left(\frac{|\tau_b|}{\tau_c} - 1 \right), & \text{if } |\tau_b| > \tau_c \\ 0, & \text{if } |\tau_b| = \tau_c, \\ C_b W_s \left(\frac{|\tau_b|}{\tau_c} - 1 \right), & \text{if } |\tau_b| < \tau_c \end{cases} \quad (3)$$

where E_0 is the erosion coefficient [$\text{kg m}^{-2} \text{ s}^{-1}$], τ_c [N m^{-2}] is the critical resuspension and deposition stress, and C_b [kg m^{-3}] is the sediment concentration at the model's bottom layer. The critical erosion stress was assumed to be 0.10 N m^{-2} for water areas, and 1.0 N m^{-2} for tidal flats and mangrove areas, while the critical deposition stress for the whole domain was 0.08 N m^{-2} . The settling velocity (W_s) was assumed to be $1 \times 10^{-5} \text{ m s}^{-1}$.

To solve the vertical mixing at the vertical sub-grid scale, the Mellor-Yamada level 2.5 turbulence closure scheme was used (Mellor and Yamada 1982). The extra turbulent mixing due to waves is not yet included in the eddy diffusivity for FVCOM; however, the small effect by waves has been discussed, and previous studies showed that wave influence is negligible within DH (INPEX 2010a, b).

In the past, c.a. before 10 years ago, the coefficients of horizontal diffusivity and viscosity were often treated as user-defined physical parameters. Therefore, to simulate sub-grid scale processes, assumptions were often required to choose the values of the horizontal eddy diffusion and eddy viscosity coefficients, which usually depend on grid size and are likely to vary in time. Many models now apply parameterizations to account for the horizontal viscosity coefficient. The well-known viscosity parameterization by Smagorinsky (1963) is applied in many hydrodynamical studies (e.g. Andutta et al. 2011, 2012, 2013a). The horizontal eddy diffusivity, K_h , is often user-defined, and in some cases calculated as a function of the grid-size (e.g. Andutta et al. 2011, 2012, 2013a). In this study, the horizontal diffusivity was adjusted to fit observed values of suspended sediment concentration against model results. The remaining numerical and physical parameters are described in more detail by Li et al. (2012) and Wang and Andutta (2012).

Initial Conditions and Simulation Scenarios

For the initial conditions, a homogeneous distribution of salinity and temperature was assumed for the whole domain, with a salinity of 33 psu and temperature of 25°C , which were constant in time (Wang and Andutta 2012; Li et al. 2012; Michie et al. 1991). Two different scenarios for the simulations were analysed. For the first scenario tidal flats and mangrove areas were applied (S_1), and for the second scenario tidal flats and mangrove areas were excluded from the domain (S_2). These simulations provide an understanding of the independent effects of tidal flats and mangroves in the transport of sediment in DH. Mangrove areas usually cause trapping of sediments (Victor et al. 2004; Wolanski and Spagnol 2000; Wolanski et al. 1998), and also affect asymmetry of tidal currents (Li et al. 2012). The sediment model was run for 40 days, from 1 October 2011 to 9 November 2011, and the sediment model started 12 h after

Table 2 Location of the current meter mooring sites, tidal gauge, transects of velocity profiles, CTP, and NTU profiles

Description	Indication in Fig. 3c	Location	Number of transects or profiles	Period of measurements (local time)
ADCP transect	a	Across East Arm	36	30/09/2007; from 15:16:00 to 17:04:00
ADCP profiles	b	East Arm (Blaydin station)	4,175	from 19/06/2009 22:50:00 to 18/07/2009 22:30:00
ADCP profiles	c	East Arm (Hudson station)	4,621	from 01/08/2009 08:50:00 to 02/09/2009 10:00:00
Tides	d	East Arm (BoM station)	847,200	from 01/05/1991 to 31/12/2010
ADCP transect	e	Across East Arm	40	26/10/2011; from 07:11:00 to 18:05:00
CTD profiles	f	Blackmore and Elizabeth Rivers	35	from 26/10/2011 06:46:00 to 27/10/2011 16:53:00
CTD and OBS transect	g1	Along Middle Arm until outer harbor	10	07/11/2012; from 10:46:00 to 13:18:00
CTD and OBS transect	g2	Along East Arm	5	06/11/2012; from 11:40:00 to 12:35:00
CTD and OBS transect	g3	Along West Arm	3	06/11/2012; from 13:11:00 to 13:50:00

The exact location of each obtained measurements is shown in Fig. 3

Model Calibration and Validation

The skill method suggested by Wilmott (1981) was applied to quantify the agreement of velocities and sea level; similar studies have applied and shown the advantages of this quantitative parameter (e.g. Andutta 2006, 2011 and Andutta et al. 2006a). This parameter was used for the final tuning of the user-defined physical parameters (e.g. diffusion coefficient, bottom roughness etc), and to determine which was the most representative turbulent closure method (e.g. method by Mellor and Yamada 1982). The skill parameter is calculated using the equation,

$$Skill = 1 - \frac{\sum |X_{model} - X_{obs}|^2}{\sum (|X_{model} - \bar{X}_{obs}| + |X_{obs} - \bar{X}_{obs}|)^2}, \quad (5)$$

where X_{obs} and X_{model} are respectively the observed and simulated properties, and $\bar{X}_{obs}$ represents the time averaged value. The skill parameter is a dimensionless quantity. It varies from 1 to zero, with 1 indicating the best fit, and zero indicating a complete disagreement between the observed and theoretical results.

To validate model results, tidal oscillation and water current measurements from different periods during the dry season were used (see Table 2), e.g. data from 2007, 2009, 2011 and 2012. Measurements were obtained at anchored stations, from cross-channel and along-channel transects. The instruments used to obtain measurements were tidal gauges, ADCP (Acoustic Doppler Current Profiler), ADP (Acoustic Doppler Profiler), CTDs (Conductivity, Temperature and Depth), and Optical Backscatter Sensors (OBS). The OBS were used to measure Nephelometer Turbid Units

the beginning of the hydrodynamical model. The first 10 days of simulation were used to generate the conditions for the following 30 days of simulation, i.e. “hot start”. The calibration and validation of tidal oscillation and tidal currents was made using simulations from different periods, but all comparisons were during the dry season (negligible fresh water inflow), and under the same tidal forcings. The cohesive sediment was considered within the whole domain, with a grain size of 0.002 mm. This fine sediment constitutes the larger part of the suspended sediment for DH (INPEX 2010a, b), and fine sediment commonly extends increasingly on estuary beds (Brenon and Le Hir 1999).

Estimation of Tidal Asymmetry

The skewness parameter γ , Eq. 4, was calculated to verify the effect of mangrove and tidal flat areas on tidal asymmetry. The tidal asymmetry parameter γ allows identification of the major factors controlling tidal asymmetry. For the skewness parameter, the tidal components M_2 and M_4 were verified to control tidal asymmetry (Li et al. 2012), and so the expression to calculate γ was:

$$\gamma_{M_2/M_4} = \frac{\frac{3}{2} a_{M_2}^2 a_{M_4}^2 \sin(2\varphi_{M_2} - \varphi_{M_4})}{\left[\frac{1}{2} (a_{M_2}^2 + 4a_{M_4}^2)\right]^{\frac{3}{2}}} \quad (4)$$

where φ and a are the phases and amplitudes of the astronomical tides M_2 and M_4 , respectively.

(NTU), which were converted into suspended sediment concentration SSC.

Simulated tides and water currents were evaluated using the skill parameter, and some comparisons of time-series are shown in Fig. 5a, b. From these figures it is evident that the model satisfactorily reproduces the observations of tidal oscillation and currents. Tidal data obtained at Blaydin, Hudson and BoM stations were used to verify the model results (see Fig. 3). The Nortek ADCP data obtained at the Blaydin and Hudson stations were from a period of over 1 month at 10 min intervals, while data at the BoM station were from a longer period (see Table 2). Figure 5a shows the predicted tides, which agree well with the field data from the Blaydin and BoM stations (positions b and d in Fig. 4c). Skill values of 0.95 and 0.98 were calculated from the comparison between theoretical and observational data of tides. For Hudson station the tides also showed good agreement, with a skill value of 0.97 (position c in Fig. 3c, but comparison not shown). The model also performed well in predicting the water currents at Blaydin station near the surface, middle and bottom (Fig. 6b). The skill values over ~0.90 were calculated for Blaydin station from comparison between along-channel and across water velocities. Only the along-channel orientation is shown; the across-channel component of velocity was relatively small and thus is not shown. For Hudson station, the simulated velocity profiles showed good agreement with observations (figure not shown), with the skill value at the different vertical layers calculated to be ~0.90. Transects obtained across EA at locations (a) and (e) are shown in Fig. 3c, and measurement periods are described in Table 2. These transects were used to evaluate model performance of tides and the cross-sectional structure of water currents. As expected, the tides showed good agreement; however, the skill value was not calculated, because the transects were made only a few times and the period between each was not consistent. Figure 6c shows that the model results reproduce the currents across EA well, as seen at the transect from a single moment during flood currents.

CTD profiles made along EA, MA and WA were obtained in order to support the assumption of constant values for salinity and temperature during the dry season (four positions indicated by f, and locations at transects g1, g2 and g3 in Fig. 4c). From (f), the average salinity from the two sites along the EA was ~35.7 psu, and the salinity difference between these two locations was less than 0.3 psu. Along the MA the mean salinity from the two sites was ~36.3 psu, and the salinity difference between these two locations was less than 0.5 psu. The average temperatures were 30.1 and 30.6 °C in EA and MA, respectively.

During November 2012 at the end of the dry season, profiles of salinity and temperature were obtained along the three arms (g1, g2 and g3 in Fig. 4). All profiles were

obtained during neap tides, during the short period between high tide and peak ebb currents. The salinity profiles were observed to be nearly well-mixed in all locations. The maximum vertical salinity gradients in the East and West Arms were observed at the furthest upstream locations, but did not exceed 1 psu between surface and bottom. Along the MA, the salinity was observed to increase from ~34.2 psu at coastal areas to ~36.2 at the furthest upstream location. For the WA, the average salinity using data from the first two locations close to the arm entrance was 35 ± 0.2 psu, and ~31.5 psu at the furthest upstream location. For the EA, the average salinity calculated using data from the first four profiles was 34.2 ± 0.2 psu, and ~31.5 psu at the furthest upstream location. The average temperature of 31.5 ± 0.5 °C was calculated using data from transects g1, g2, and g3.

Tidal amplitudes of the main semi-diurnal and diurnal components (e.g. M_2 , S_2 , N_2 , K_2 , K_1 , O_1 and M_4) were calculated using the Fourier Transform (Franco and Rock 1971). The observed and predicted amplitudes are shown in Table 3. Observed amplitudes were obtained from harmonic analyses using data from 1992 to 2009. The semi-diurnal components represent nearly 78 % of the total amplitude, showing that DH is a semidiurnal environment. Model results show good agreement between measured and predicted amplitude of the main tidal components for DH. The deviations were calculated for all components (not shown). The largest deviation of 20 % was for M_4 , but this component is relatively small when compared to all seven other components from Table 2. Therefore, the model performed well in predicting the amplitude of the most important tidal components for DH.

Model Results

The model results reveal current flows in DH. Figure 7a, b show the model results of vertically averaged current velocities during flood and ebb currents in spring tides. Current speeds increase from the outer harbour to the channel, and then slightly decrease in the inner harbour. Current velocities in the arms are larger than those in the inner harbour. The peak current velocity is about 2.5 m s^{-1} in MA. For the inner harbour and arms, the water flow patterns are in accordance with the shoreline. Current speeds fall to almost zero in the mangrove areas because of the large amount of friction.

Tidal asymmetry in the harbour was calculated using Eq. (4), and shown in Fig. 6c. The skewness parameter distribution shows flood dominance in DH, and the skewness value increases from the outer harbour (0.07) to the inner harbour (0.1) and the arms (0.15).

Fig. 6 (a) Modelled tides (m), compared to measured tides at stations BoM and Blaydin (positions b and d in Fig. 3c). The skill parameter of ~ 0.98 was calculated for BoM and Blaydin stations. (b) Modelled along-channel velocities (m s^{-1}), compared to observations at station Blaydin. The skill parameter of 0.95 was calculated from comparisons

at surface, and 0.97 for the *middle* and *bottom* layers. Across-channel velocities were negligible from observation and simulation (not shown). (c) Comparison of observed (*top*) and predicted (*bottom*) along-channel velocities using data from transect shown in Fig. 3c, on 30th of September 2007

Table 3 Comparison between theoretical and observed amplitude of tidal components

Tidal component	Nature	Component name	Period (solar hours)	Observed (m)	Model (m)
M ₂	Semi-diurnal	Principal lunar	12.42	1.85	1.70
S ₂	Semi-diurnal	Principal solar	12.00	0.96	0.93
N ₂	Semi-diurnal	Larger lunar elliptic	12.66	0.35	0.29
K ₂	Semi-diurnal	Luni-solar	11.97	0.27	0.25
K ₁	Diurnal	Luni-solar diurnal	23.93	0.58	0.53
O ₁	Diurnal	Principal lunar diurnal	25.82	0.33	0.30
M ₄	Compound	–	6.21	0.05	0.04

Measurements were taken near BoM station

Fig. 7 (a) Ebb currents, and (b) flood currents during spring tide. (c) Tidal asymmetry calculated by the skewness parameter (Eq. 4)

The skewness parameter was also calculated using the observed current velocities at Station Blaydin, γ_{obs} , and is shown in Table 4. The along the channel currents indicate a flood dominance at all depths. In DH, γ_{obs} was verified to be slightly larger than the model predicted γ , ca. ~ 0.1 . The formation of Estuarine Turbidity Maxima zones is commonly observed in macro-tidal estuaries (e.g. Manning et al. 2010; Uncles and Stephens 2010). This is because strong water currents in macro-tidal estuaries can suspend large amounts of fine sediment from the bottom, and thus SSC increases to high values. Therefore, ETM zones can be formed even under conditions of low sediment input from upstream locations. ETM zones have sediment concentrations in the water column that are typically one or two orders of magnitude higher than upstream and coastal areas

(Nichols and Biggs 1985). The understanding of ETM zones is important for the local ecosystem because some toxic substances, e.g. metals, tend to attach to fine sediment particles, which are often the most mobile sedimentary fraction in estuaries (Doxaran et al. 2009; Taylor and Hudson-Edwards 2005, 2008; Thonon 2006). ETM formation is driven by different processes such as tidal currents, tidal asymmetry, salinity stratification, density driven currents, waves, water density stratification due to salinity, temperature and SSC (Manning et al. 2010; Uncles and Stephens). Additionally, bathymetry modulates water circulation and therefore may affect the location and formation of ETM zones (Brenon and Le Hir 1999).

Figure 8a shows some snapshots of the vertical distribution of SSC during spring tides along the MA and towards the coastal zone (see transect iii indication in Fig. 4b). Two ETM zones can be observed from the simulation results, with the upstream ETM zone having SSC up to ($\sim 0.3 \text{ kg m}^{-3}$), which is nearly double the suspended sediment concentration of the ETM zone along the entrance channel ($\sim 0.2 \text{ kg m}^{-3}$). The ETM zone near the channel moves nearly 10 km between low and high tides. The higher SSC in the ETM zone along the MA is predicted to remain in this channel; however, a decrease in SSC is shown during high tides. The vertical stratification of SSC is negligible during spring tides. In contrast, during neap tides the vertical mixing decreases (figure not shown), and thus SSC showed some stratification through the water column.

Figure 8b shows the SSC seen at the sigma bottom layer, obtained from the simulation considering scenario S₁, for spring tides. The formation of two ETM zones in DH was predicted. One ETM zone is formed along the MA, and another is observed in coastal areas near DH entrance. The formation of these two ETM zones is due to the strong bottom stress by the tidal currents, with water speeds that easily exceed 1 m s^{-1} . The ETM zone formed in the MA shows higher SSC than at the harbour entrance (nearly double). This high SSC is caused by the combined effect of strong currents due to the shoaling effect within the MA, and the availability of fine sediment particles. In spring tides, the SSC along the MA reaches values as high as $\sim 0.3 \text{ kg m}^{-3}$, and values of $\sim 0.2 \text{ kg m}^{-3}$ at the channel's

t4.1 **Table 4** The skewness parameter γ of observed currents at Station Blaydin

t4.2	Vertical layer and (depth in metres)	Main velocity skewness
t4.3	1 (1.8)	0.16
t4.4	2 (2.8)	0.12
t4.5	3 (3.8)	0.11
t4.6	4 (4.8)	0.11
t4.7	5 (5.8)	0.12
t4.8	6 (6.8)	0.13
t4.9	Average 1–6 layers	0.12

Fig. 8 (a) Vertical distribution of suspended sediment concentration (SSC) from transect (iii) in spring tidal cycle (see Fig. 3b). *Left and right side of figure denote respectively coastal and upstream area. HW and LW refer to high water and low water, respectively. (b) Bottom distribution of SSC (kg m⁻³) in spring tidal cycle. HW and LW refer to high water and low water, respectively*

Fig. 9 (a) Vertical distribution of suspended sediment concentration (SSC) from transect (iii) in neap tidal cycle (see Fig. 3b). *Left and right side of figure denote coastal and upstream areas, respectively. HW and LW refer to high water and low water, respectively. (b) Bottom distribution of SSC (kg m⁻³) in neap tidal cycle. HW and LW refer to high water and low water, respectively*

Future Implications for the Marine Ecosystem of Darwin Harbour

Many estuaries in Europe have sequestered pollutants on the fine sediment, and some of this sediment-bound pollution is observed to date from around the time of the industrial revolution (Den Besten et al. 2003; Löser et al. 2001; Clark et al. 1997). In the past few years, DH has undergone considerable developments because of natural resources from the Ichthys Gas Field (INPEX 2010b, b). Intensive dredging activities are currently taking place, but little is known about threshold limits of high SSC that the DH marine ecosystem can sustain. Some other muddy, macro-tidal and mangrove fringed harbours in Asia (e.g. Ho Chi Minh City and Jakarta), are observed to have high concentrations of pollutants buried within their mud (Rochyatun and Rozak 2008; Minh et al. 2007; Hong et al. 2000; Williams et al. 2000). One would fear a similar future for the DH marine ecosystem, because a large pollution event may result in a considerable portion of pollutants to be buried in the mud. If this was to happen, the length of time the pollutant would be trapped within mangrove areas, and therefore affecting marine species such as the mud crab, local birds, and fishes would be of concern. There is some fear that climate change will result in sea level rise (IPCC 2007; McInnes et al. 2003), and thus cause changes to local

hydrodynamics and sediment transport. Sea level has risen globally nearly 1.7 mm year^{-1} during the twentieth century, caused by thermal expansion of melting glaciers and ice caps (IPCC 2007). In addition, sea level is still projected to rise at a larger rate than it has in previous decades. Not all areas, however, have the same sea level rising rate, and some areas are even reported to have a decreasing sea level. These sea level changes raise concern about the possibility of the sediment-trapped pollutants being released back into the water in European estuaries, and thus negatively impacting the local marine ecosystem. Unlike the estuaries in Europe, DH has only undergone most of its development recently, and its future development seems to be connected with exploitation of natural resources. DH is considered a largely unmodified marine environment (Estuary Assessment 2002: Estuaries by Australian Natural Resources Atlas). Therefore, it is too early to infer the hypothesis that similar consequences to that of European estuaries would also occur in DH.

From our results we demonstrate that the sediment transport of small particles in DH is driven by flood dominance, which is therefore affected by wet/dry areas such as mangroves and tidal flats. Therefore, mangrove areas of DH may function as a sediment trap, and if the trapped sediment carries pollutants one would expect conditions similar to many European estuaries. Additionally, the reclamation of mangrove and tidal flat areas may increase tidal asymmetry (Wang and Andutta 2012; Li et al. 2012), increasing flood dominance, and subsequently increasing the rate of landwards sediment transport. All port developments in Darwin are located in EA; because of this, land reclamation in the next few decades would occur along EA. Nevertheless, if land reclamation was to happen for the EA area, one would propose two scenarios: the increased flood dominance with reduced mangrove areas in EA would result in, (a) waters of DH having higher SSC because of reduced deposition areas, (b) increased sediment deposition rates in the remaining mangrove areas (i.e. along MA and WA), (c) the combined effect from (a) and (b).

Unlike European estuaries where boundary forcings do not include cyclone events, DH is occasionally subject to cyclonic activities in the wet season (Ramsay et al. 2008; Hastings 1990; Nicholls, et al. 1998; Nicholls 1984), which are often followed by intense floods. However, these cyclonic activities are capable of flushing only a small fraction of the sediment from within the mangrove areas; therefore, if mud pollution occurs in the mangroves in DH, it is likely to be permanent like the coastal wetlands in Europe and Asia. Although these cyclonic events are projected to increase in intensity in Australia (McInnes et al. 2003), mud pollution in mangroves is predominantly relieved by bioturbation, mainly by crabs. There are no data on this process for DH.

Conclusions

The water circulation and sea level oscillation in DH was accurately simulated by the model, and our water circulation results concur with other field studies and numerical simulations using structured and unstructured models (e.g. Li et al. 2012; Williams 2009; Williams et al. 2006). Our model results would be adequate for simulating hydrodynamics in harbours and predicting suspended sediment transport patterns. Currents speeds increase from the outer harbour to the channel, and then decrease in the inner harbour. Peak currents of about $\sim 2.5 \text{ m s}^{-1}$ occur in the MA. The sediment transport pattern is revealed comprehensively, and areas of high suspended sediment concentration were observed from simulations.

This study shows that for scenario S_1 , two Estuarine Turbidity Maxima (ETM) zones are expected to form in DH during spring tides, one in the MA and another near the entrance of the bay. These ETM zones are transported by flood currents (landward direction) and ebb currents (seaward direction). During spring tides, the vertical structure of SSC is well-mixed near the peaks of the flood and ebb currents. In contrast, during neap tides the two ETM zones vanish and a small vertical gradient of SSC is predicted near high and low tides. From scenario S_2 , the ETM zone along the MA disappears and the maximum SSC within DH is considerably reduced.

Our simulations used a variable grid-size model that allowed for a high resolution prediction of water circulation within mangrove areas, tidal flats and narrow channels, as well as wet/dry grid elements for all mangrove and tidal flat areas. Our measurements have shown that salinity and temperature fields can be treated as uniform during the dry season, because observed values showed little time and space variation of these parameters during the dry season, and the minor density-driven currents are limited to the upper reaches of the rivers of DH.

In the future, DH is likely to accumulate polluted sediment. Polluted fine sediment that predicted to be trapped within mangrove areas, and only a small fraction is expected to be flushed out during cyclone events. Thus this fine sediment may remain trapped for many years. Because cyclone activities are not effective mechanisms to flush out fine sediment from DH, the likely result is that similar conditions to many European estuaries, where pollutant sediment has been found to be buried since the industrial revolution. Additionally, the increased tidal asymmetry would cause higher rates of deposition within mangroves and other areas of the harbour, and would also increase the average suspended sediment concentration of DH. Therefore, the

trapping of polluted sediment within mangrove areas combined with increased suspended sediment concentration in the estuarine waters would negatively impact marine species. Additionally, if sediment pollution affects the mud crabs and many other local marine species that are responsible for local bioturbation, trapping of polluted sediment would increase further.

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